FINAL REPORT

FEASIBILITY STUDY OF A 120-INCH ORBITING ASTRONOMICAL TELESCOPE

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J. W. FECKER DIVISION AMERICAN OPTICAL CO.

FINAL REPORT

FEASIBILITY STUDY OF A 120-INCH ORBITING

ASTRONOMICAL TELESCOPE

ABSTRACT

A preliminary study has been made on the Feasibility of a Large (120-Inch Diameter) Diffraction Limited Orbiting Telescope. The following areas are discussed: Optical Design, Primary Mirror, Optical Working and Testing, Alignment, Structure, Thermal Analysis, Micrometeoroid Damage, and Guidance Inputs. Possible approaches are given for the solution of some of the more difficult problems.

APPENDIX I

TASK ORDER NAS1-1305-18

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FEASIBILITY STUDY OF A 120 INCH ORBITING ASTRONOMICAL TELESCOPE

1.0 INTRODUCTION

This is the final report on a study to determine the feasibility of a 120" diameter orbiting astronomical telescope as part of the "Man in Space" program. The aspects of the problem to be studied were specified in Task Order NAS1-1305-18, attached as Appendix I.

The telescope has been shown to be feasible in that much of the required hardware falls within the present state-of-the-art. To demonstrate the feasibility, a telescope is described that would be adaptable to perform a great variety of experiments. Complete design of the telescope was not attempted. In those areas covered by design work, the design was not optimized beyond that needed to demonstrate feasibility. The telescope is generally of Cassegrain configuration with an f/2 primary mirror. Optical configurations are listed in Table I and include a range of focal ratios from f/2 to f/100.

A structure of aluminum alloy is provided; it will be impractical to thermally shield the structure sufficiently to hold the position of the secondary mirror within tolerance. However, an alignment system is provided that will maintain the position of the secondary mirror within proper limits despite thermal distortion of the structure. Fields for most of the configurations are large enough that there is a high probability that off-set guiding on stars within the field can be employed for any experiment.

The greatest advancement from the state-of-the-art is in the primary mirror. An f/2 paraboloid, 120" in diameter and of diffraction limited performance represents a task of considerable magnitude. However, there are very firm reasons for believing that this mirror can be made. The mirror would be made of beryllium metal coated with Kanigen to provide a polishable surface. A manufacturing sequence and testing methods to be used in producing this mirror are described.

Measurement of the position of the secondary mirror with respect to the primary mirror requires the use of an interferometer operating over considerable path length. A laser light source will make such an interferometer practical although the interferometer may require some development work.

An artists conception of the possible appearance of the completed telescope is shown in Figure 1-1. While this sketch may be technically inaccurate, the relative sizes of the man and the telescope are approximately correct.

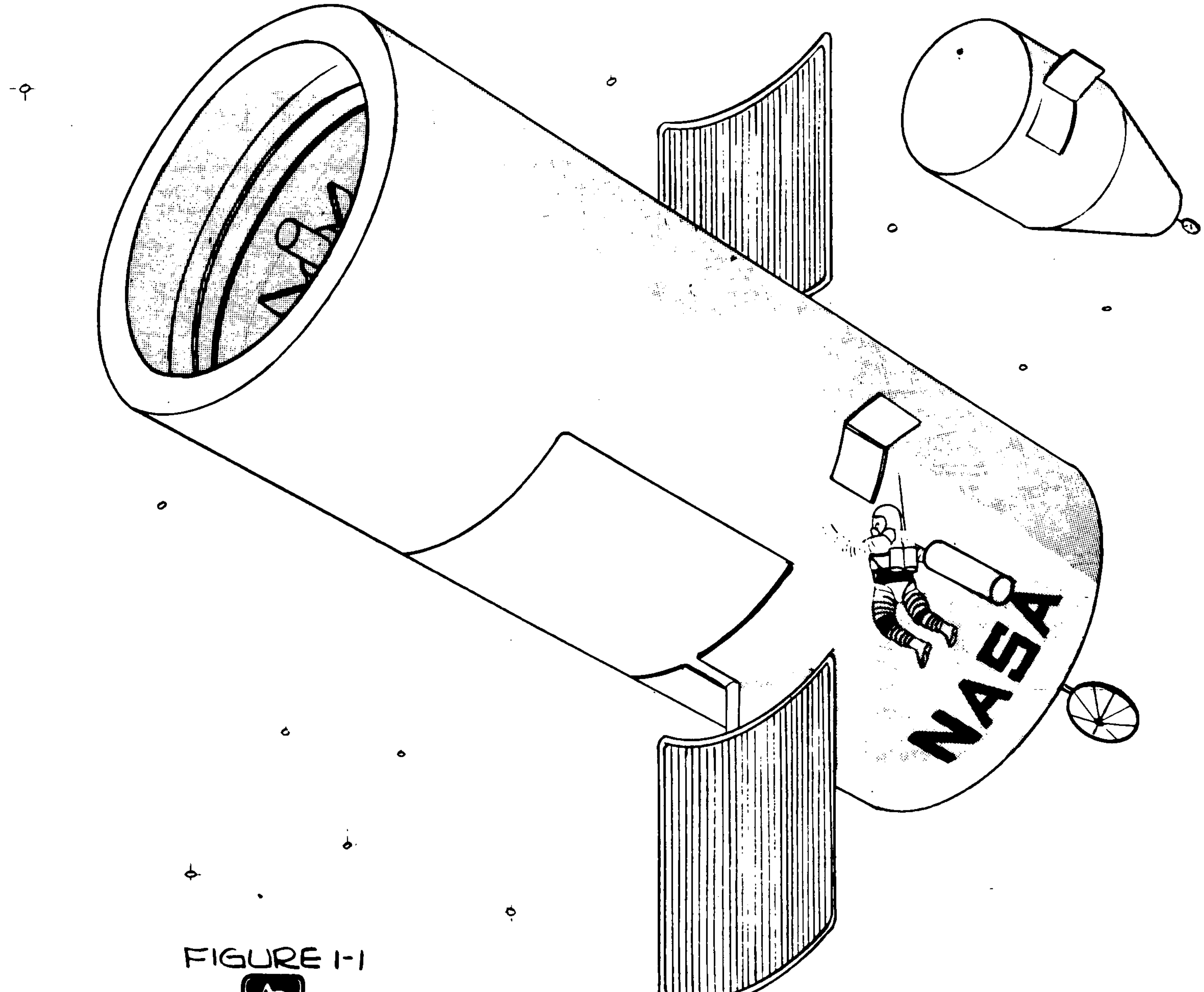

FIGURE 1-1

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Optical Configurations

TABLE 1-1

Focal Ratio	Diffraction Limited Field* (full field) Angular	Linear	Space Available at Focal Plane
2 (Prime Focus)	4 arc sec	.005-in	Up to 10 x 10 - Used for light gathering
8(Cassegrain)	1 min	0.3-in	16 X 16
10(Catadioptric)	46 min	16.5-in	16 X 16
15(Cassegrain)	3.3 min	1.8 in.	16 X 16
30(Cassegrain)**	2 min(flat field)	2.16	16X16
	16 min(curved field)	17.3	16X16
100(Catadioptric)	4.5 min	16.2	16X16

* All aberrations fall within the Airy disk

** Field curves about 1" at a distance 8.6 in. off axis. This could be corrected by refracting elements close to the focal plane for a more limited spectral range.

2.0 OPTICAL DESIGN

Optical configurations for the telescope are sketched in Figures 2-1 through 2-6, and are listed in Table I. The all reflecting systems are of Cassegrain configuration with the f/2 paraboloidal primary mirror and hyperboloidal secondary mirrors giving effective focal ratios of f/8, f/15 and f/30 at the focal plane 40 inches behind the apex of the primary mirror. With the Cassegrain configuration, the field is normally limited by coma. It is interesting to note that with the f/30 configuration, the field is slightly curved. The small secondary of the f/30 configuration also allows the system to be fully shielded against light passing directly to the focal plane. This shielding would not be necessary for most astronomical work, but would be necessary if the telescope were to see a wide bright field of view, for example, in photographing detail on the moon.

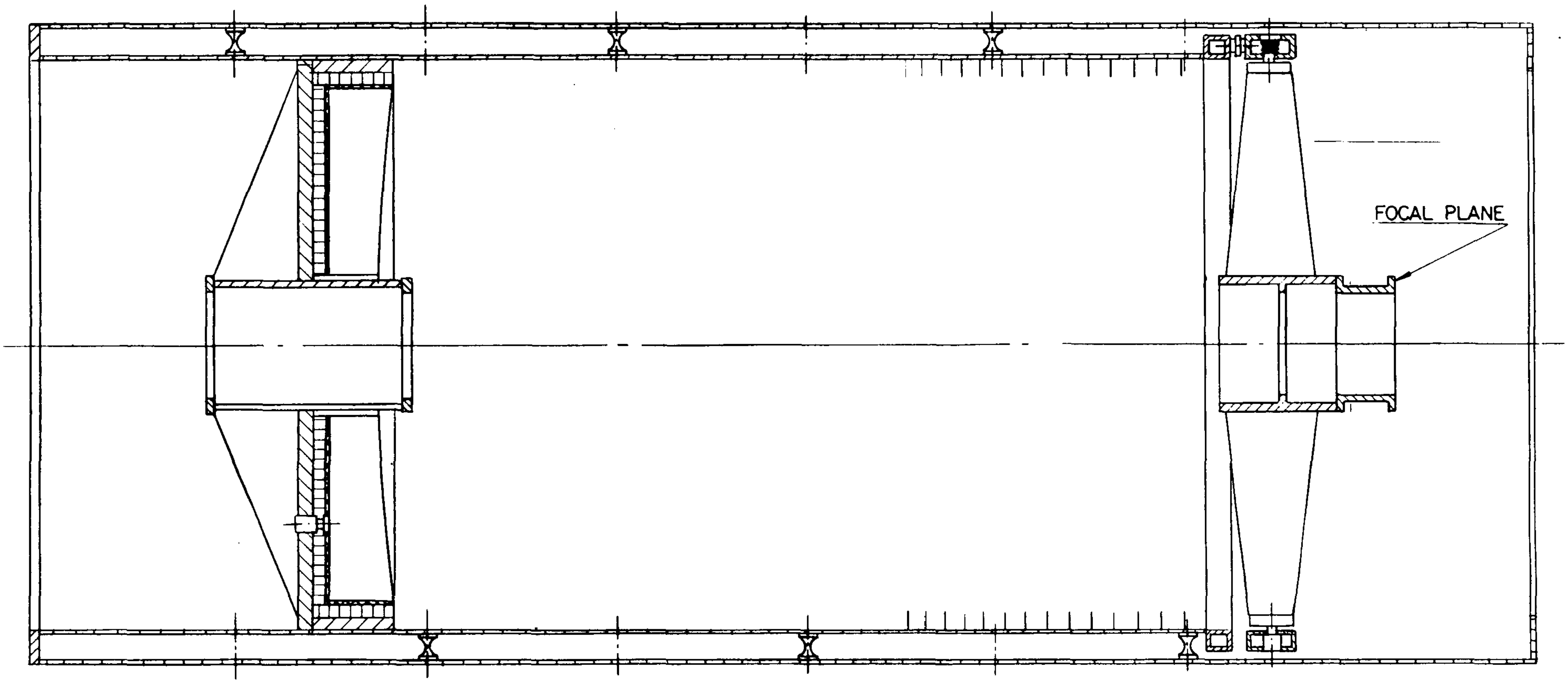
Since a paraboloidal primary is used, experiments are possible at prime focus. The extremely small, well corrected field makes the prime focus most useful for experiments in which the telescope is used for its light gathering power, and in which resolution is not important.

In the configuration shown in figure 2-3, two refracting doublets are added to the f/8 Cassegrain mirrors to obtain an effective f/10 focal ratio and diffraction limited performance in the visible spectrum over a 46 minute total field. The focal plane for this configuration, which is mounted on an extension piece, lies slightly behind the focal plane for the Cassegrain arrangements.

The refracting elements have some aspheric surfaces. In the calculations made during this study (to show feasibility) all the aspheric surfaces were conic sections; however, it may be necessary to use one or two arbitrary aspherics to finalize the design.

Addition of a negative doublet (Barlow lens) to the f/30 Cassegrain system converts it to an effective focal ratio of f/100 (as shown in Figure 2-5). The same shielding can be applied to both the f/30 and f/100 configurations, and the focal plane is moved back by the Barlow lens.

The range of focal ratios is greater than that normally provided, and should satisfy the needs of most experiments. In addition to the configurations already discussed, there remains the possibility of apodization for measurement of extremely close binaries. This is discussed in Appendix II and would be accomplished by adjusting the reflectivity of a secondary mirror. This would allow the telescope to operate with its full light gathering power for most of the experiments.



120-INCH ORBITING TELESCOPE FOR N.A.S.A.

f2 OPTICAL CONFIGURATION

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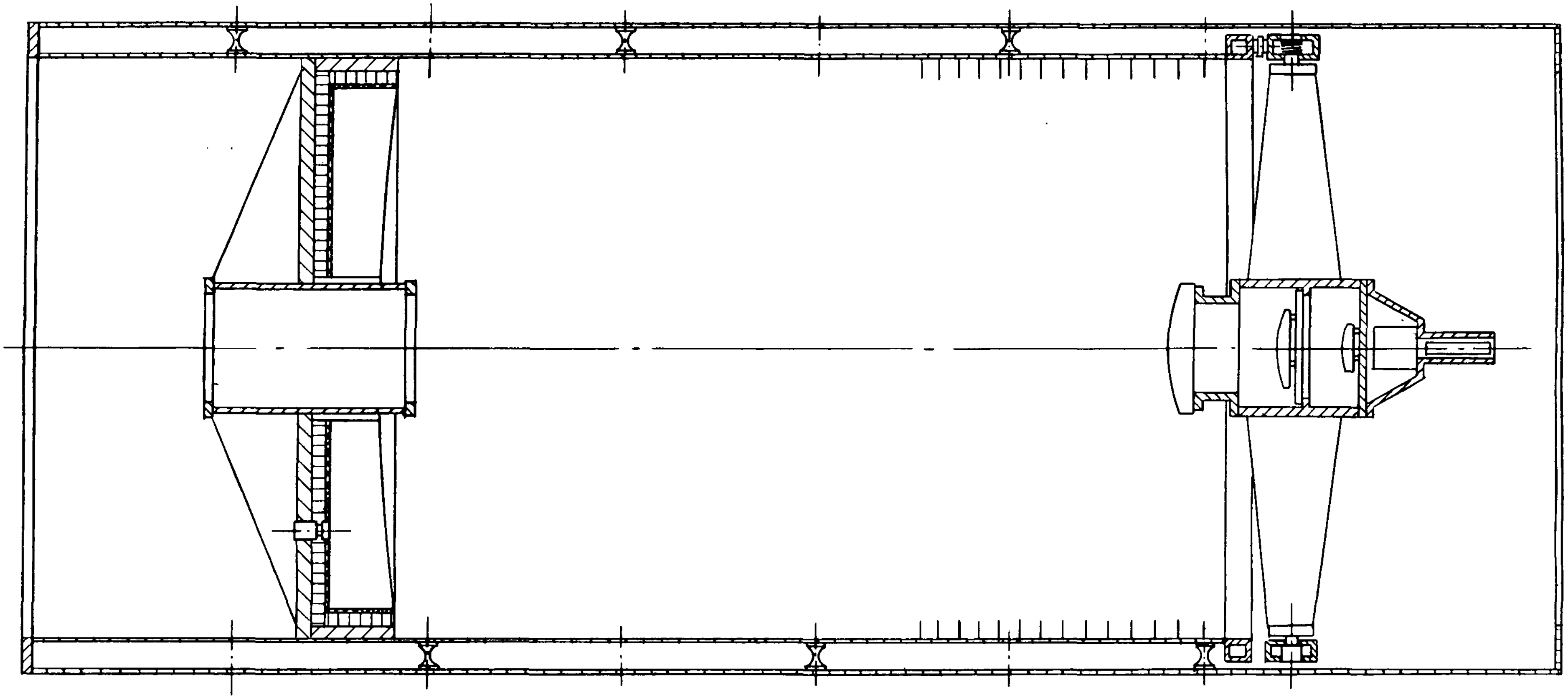
FIGURE 2-1



120-INCH ORBITING TELESCOPE FOR N.A.S.A.

f 8 OPTICAL CONFIGURATION

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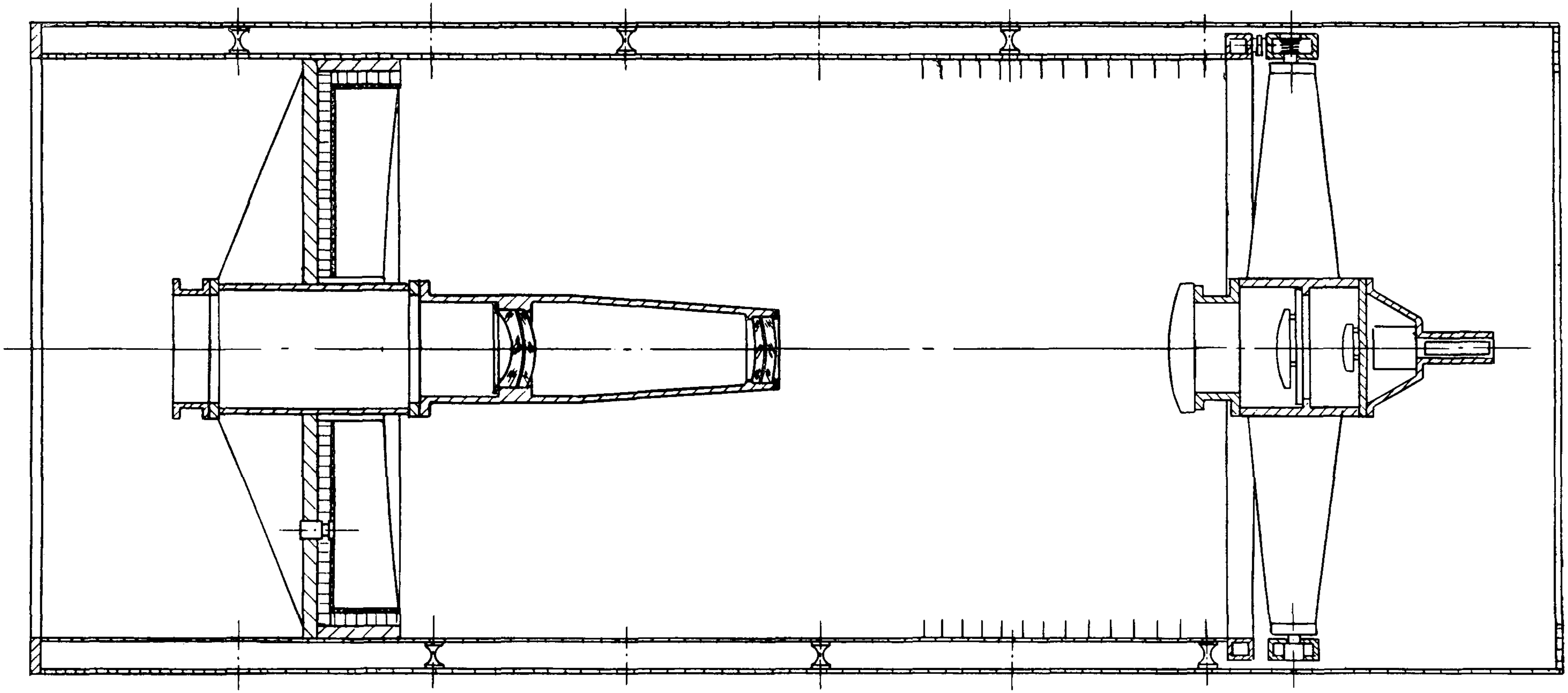
FIGURE 2-2



120-INCH ORBITING TELESCOPE FOR N.A.S.A.

f 10 WIDE FIELD OPTICAL CONFIGURATION

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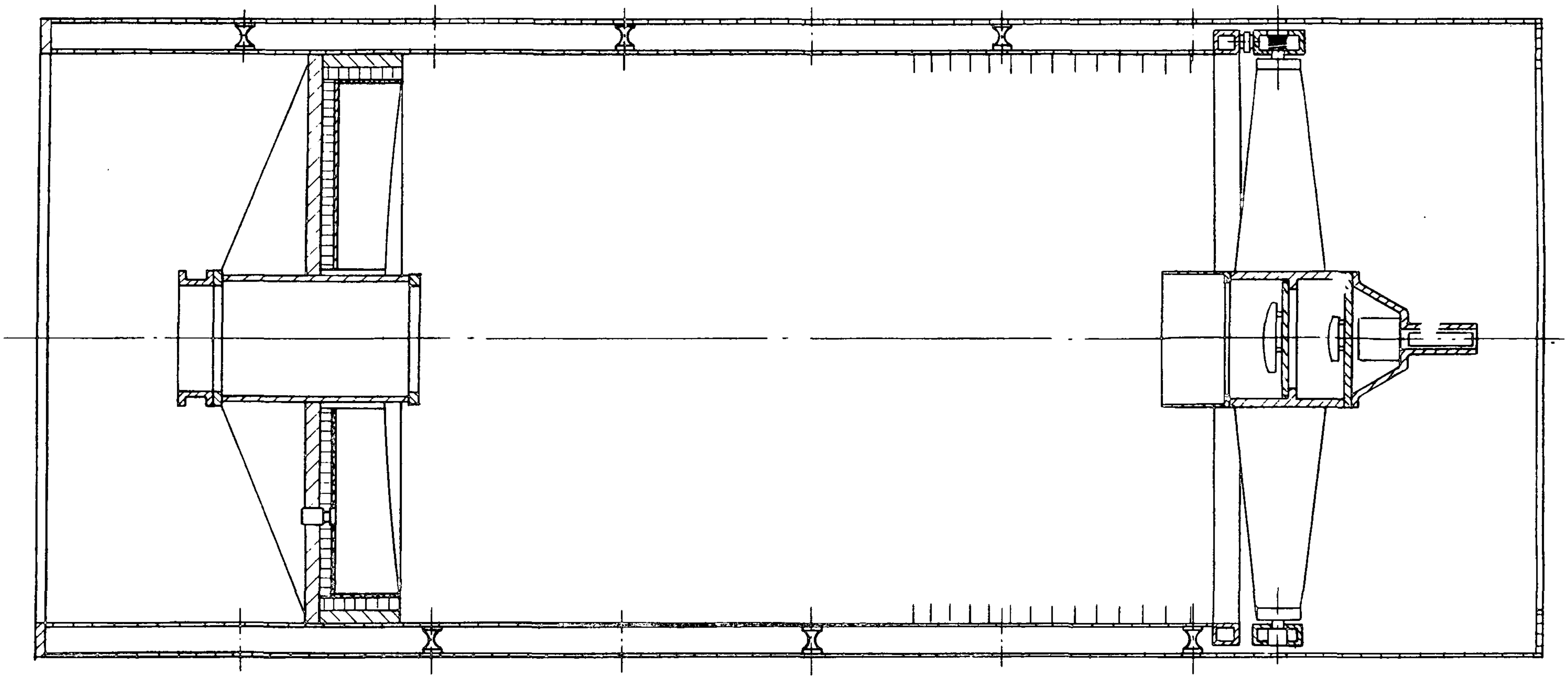
FIGURE 2-3



120-INCH ORBITING TELESCOPE FOR N.A.S.A.

f 15 OPTICAL CONFIGURATION

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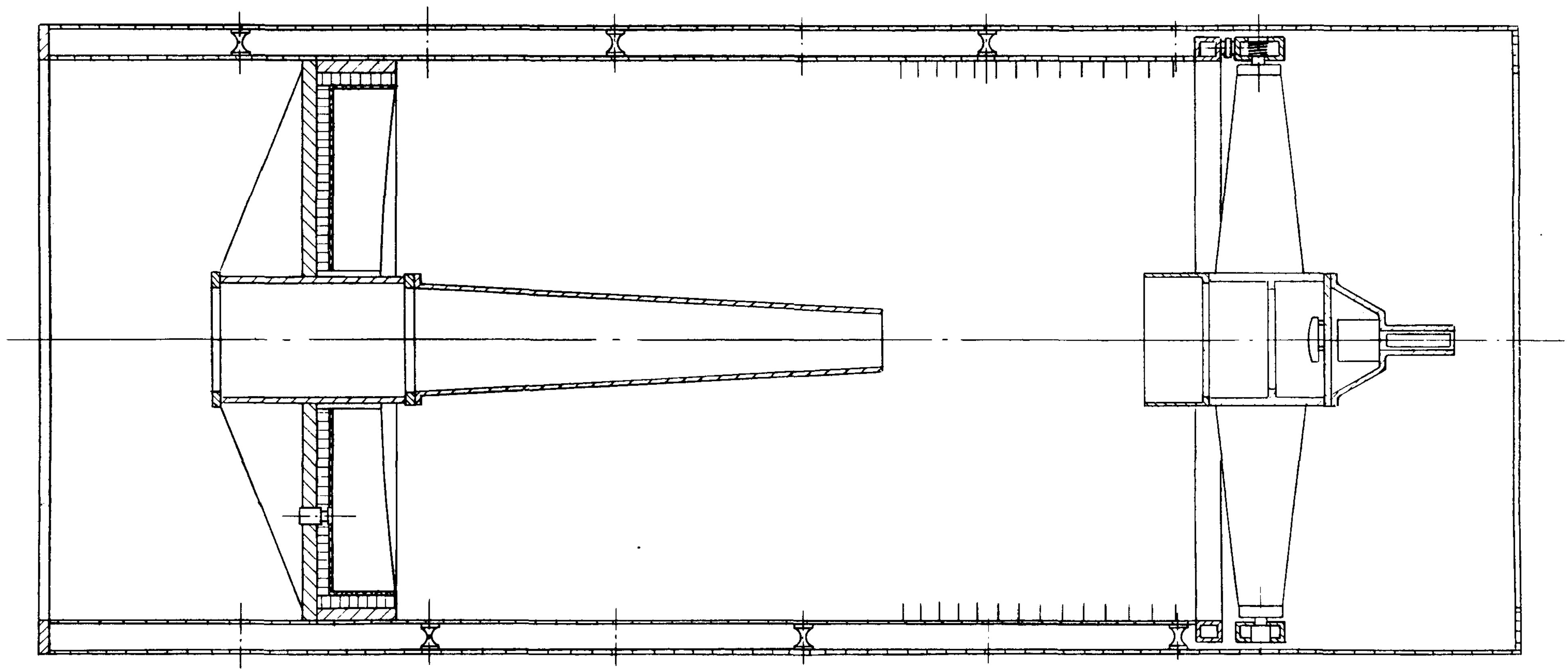
FIGURE 2-4



120-INCH ORBITING TELESCOPE FOR N.A.S.A.

f 30 OPTICAL CONFIGURATION-FULLY SHIELDED

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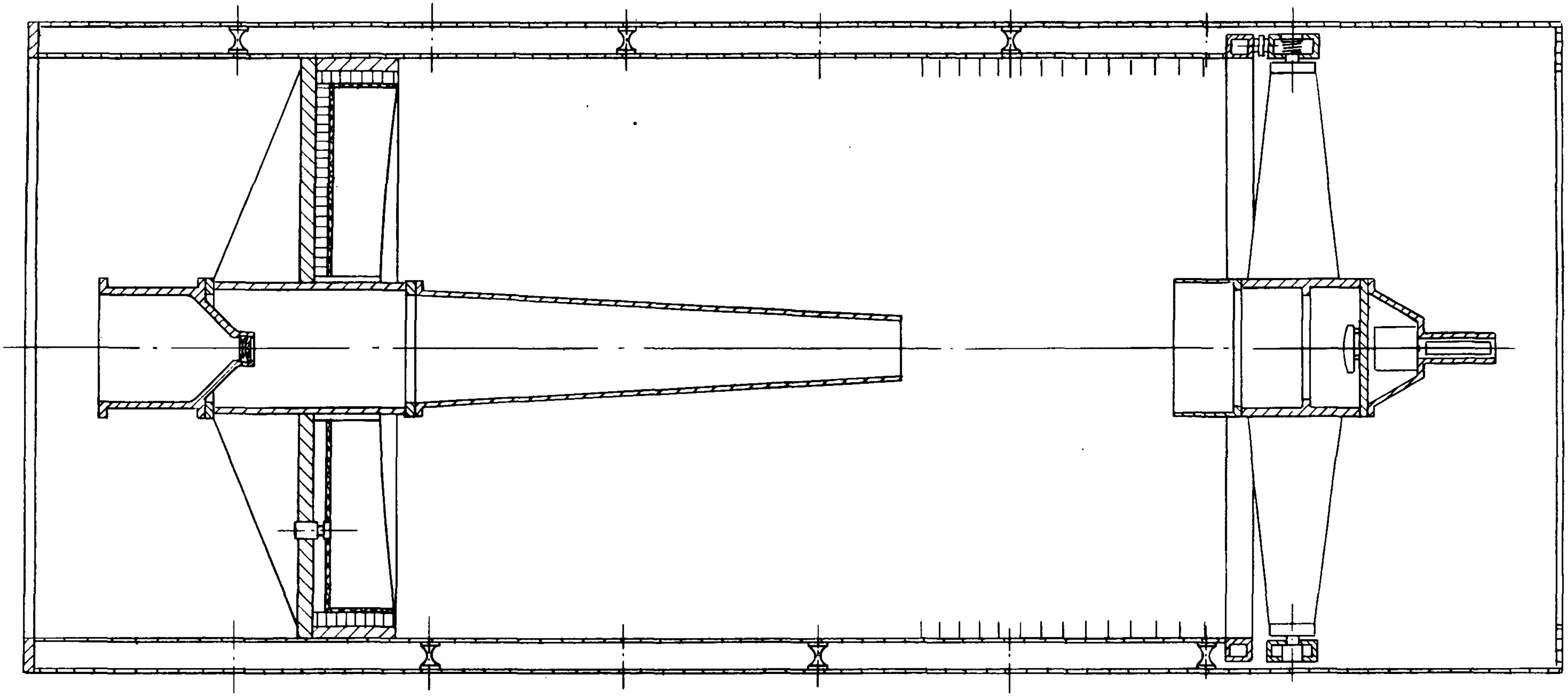
FIGURE 2-5



120 INCH ORBITING TELESCOPE FOR N.A.S.A.

f100 OPTICAL CONFIGURATION FULLY SHIELDED

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FIGURE 2-6

3.0 DESIGN OF THE PRIMARY MIRROR

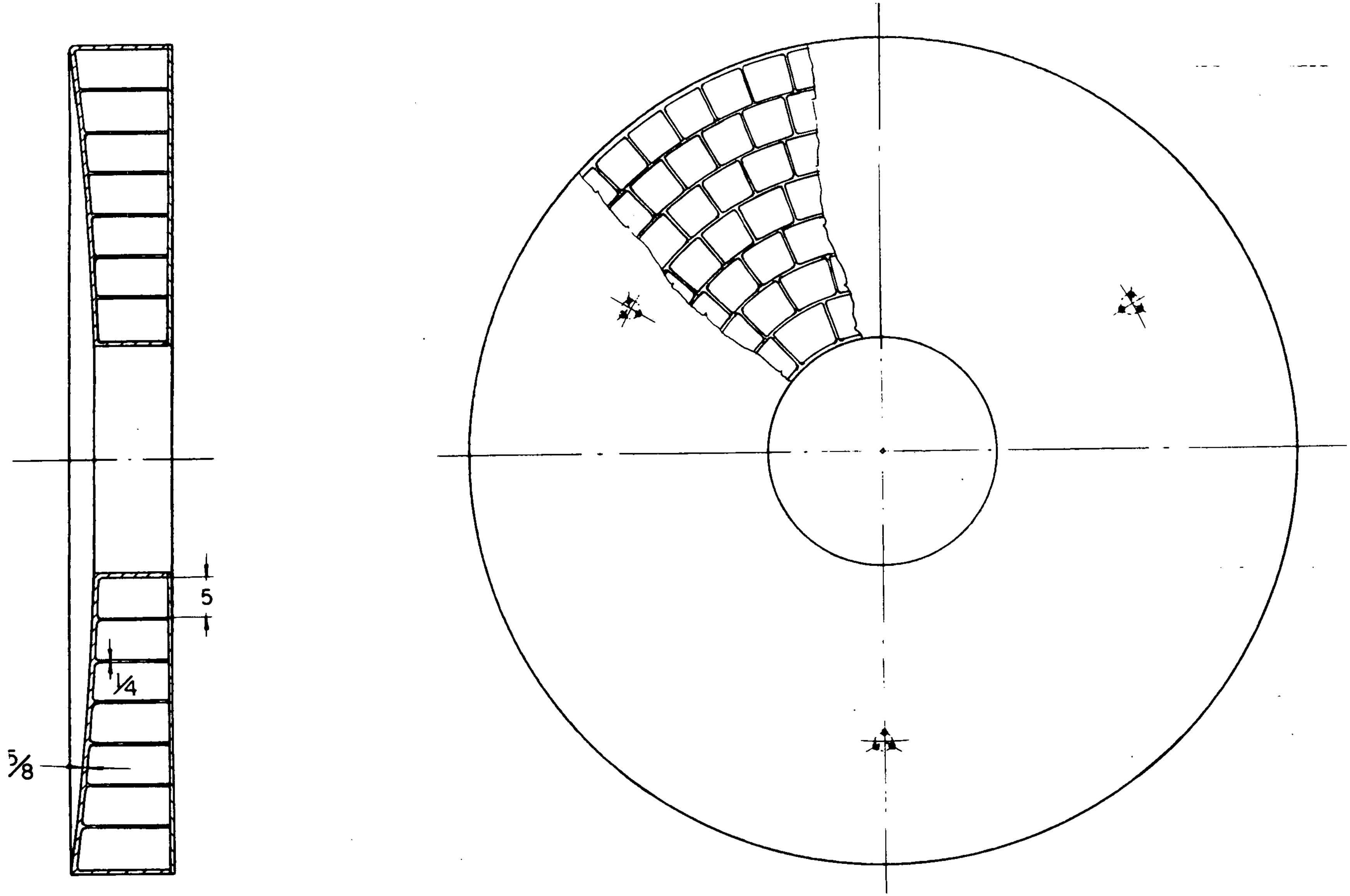
Traditionally, mirrors for astronomical telescopes have been made of solid blanks of glass, pyrex, or fused quartz. These materials can be polished easily, have a low coefficience of expansion, and are quite dimensionally stable. However, when considering a large mirror for space use, the relatively high weight of the solid ceramic blanks becomes a great disadvantage. A means of producing a light-weight optical quality mirror is therefore required if the telescope is to be feasible.

Considerable progress has been made in making fused quartz mirrors of lightweight construction at the Corning Glass Company. As part of this study, Corning was contacted to determine if a 120" diameter, F/2, lightweight fused silica mirror blank would be feasible. Corning feels that such a mirror blank could be made, and gave a "ball park" quote of $1.25 million. Their method of construction requires that both the front and back face plates of the sandwich construction be sagged. Face plates would have to be made by fusing together segments of 1/2 inch to 2 inch thick silica plate. The ribs separating the two face plates would be non-continuous. Total weight of the mirror would be about 5,000 pounds, and the time required to make the blank would be about one year from the time the order for the designed blank was placed.

Another approach to lightweight mirror construction is to use a metal material. Of all the metals available, the most desirable combination of properties is obtained with beryllium. Beryllium has a thermal coefficient of expansion of about $6.1 \times 10^{-6}/^{o}F$, which is much greater than that of the ceramic materials. However, the much greater thermal conductivity and thermal diffusivity would ensure that gradients which would distort the mirror are kept to a minimum. Calculations show that for the same geometric configuration, and a given flux environment as might be found in space, the thermal distortions of the beryllium mirror at $70^{o}F$ are far less than that of a fused silica mirror. In addition, the low density of the beryllium makes it considerably lighter than the fused silica mirror, and the modulus of elasticity of 40×10^{6} psi ensures that the mirror is more rigid in resisting mechanical loads than a similar quartz mirror.

Brush Beryllium Corporation, and Beryllium Corporation of America were contacted to determine the feasibility of making a 120 inch diameter mirror blank. Brush Beryllium proposed that such a blank could be made from a vacuum hot pressing of their QMV metal. Beryllium cannot normally be cast into useful forms because excessively large grains are formed. The normal procedure is to machine the beryllium to form a powder of fine chips. The powder is then consolidated by heat and pressure into a solid material. The principal impurity of the resulting product is beryllium oxide, which does not react with the base metal, and therefore does not introduce any instability into the product. Brush Beryllium now has a furnace and press capabity for compacting disks up to about 80" in diameter. They feel that with larger facilities, a 120" diameter blank could be made. The facility required would cost approximately $500,000. The finished machine blank, made roughly to the design shown in Figure 3-1, would cost slightly over one million dollars.

Beryllium Corp. believed that the blank could be made with existing facilities, but some development work would be required to develop the specific method. They propose that the piece might be made by one of three methods. The first would involve making the pressing to less than 100% density using the Lyman Gordon 50,000 ton forging press. Small samples could be made at relatively low cost to determine if this could produce a satisfactory product. The second method would involve making a smaller diameter pressing and forging it in increments (a hand forging process) to the required 120" diameter. In this case, tests would have to be made to demonstrate that the forged product would have the same stability that has been observed in the vacuum hot pressings. The third



120-INCH ORBITING TELESCOPE FOR N.A.S.A.

BERYLLIUM PRIMARY MIRROR

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FIGURE 3-

method would involve the combined pressing and back extrusion. The powder would be sealed into a steel can (which is the normal practice in working beryllium) and would then be pressed between a waffle shaped and a flat die. The metal would extrude back between the segments of the waffle shape die to form the ribs of the mirror. At the same time, the front face plate would be formed by a compacting operation. The back face plate would have to be made separately.

4.0 OPTICAL WORKING AND TESTING

The most difficult tasks in the manufacture of the 120 inch orbiting telescope will be that of making the f/2 primary mirror. This mirror is a paraboloid which must be figured to 1/10 wave, or to about two millionths of an inch. A mirror of this size has never been figured to such accuracy. However, there are substantial reasons to enable one to consider this task as feasible within the next two or three years. For terrestrial telescopes, there has been no need to attempt to obtain diffraction limited performance of the optics because of the basic limitations in seeing through the atmosphere. The 120 inch mirror at the Lick Observatory has been contour plotted, and it is felt that its figure could be improved, but no improvement in the performance of the telescope would result. Thus, there has been no effort to make the best mirror possible.

Another determining factor to very precise figuring of large conventional optics is the great length of time required for the large blanks to reach thermal equilibrium after working (and during use in the observatories), which results in long waiting periods while very little optical work can take place during the final figuring. With the beryllium material used in the present mirror, the time required to reach thermal equilibrium is significantly reduced.

This effect can be observed on the smaller beryllium mirrors that are currently being made in a number of optical shops. The time required to stabilize the figure of a beryllium mirror is only a few minutes, while a similar quartz mirror might take several hours.

As the high speed of the parabola is increased, the difficulties encountered in manufacturing and testing are correspondingly increased. The traditional method of producing a parabolic mirror first involves grinding and polishing to a near spherical shape. Tests would then insure that the surface was a true surface of revolution within acceptable limits. Parabolizing would follow, being accomplished by polishing with small pitch laps. The center would be deepened until tests verified that the surface was a paraboloid.

This procedure is quite useful on slow paraboloids where the paraboloid very closely approximates a sphere. As the speed and size of the parabola is increased, the deviation from a spherical shape is increased. The 200 inch f/3.3 parabola of the Mt. Palomar telescope deviates from its vertex sphere by 0.005 inch. This mirror was parabolized by alternately grinding and polishing until tests showed that the figure was very nearly the desired parabola. Then final figuring of the mirror was accomplished by polishing.

The 120 inch f/2 parabola deviates from its vertex sphere by 0.015 inches. Since the Kanigen coating applied to the beryllium to permit polishing will be only 0.010 inches thick, the parabolic curve must be machined into the blank before it is Kanigen coated. Tolerances on the machined surface are critical to allow the maximum amount of Kanigen for optical working.

The blank, after being Kanigen coated, should again have the paraboloidal shape generated in the surface. This operation will minimize astigmatism and obtain a surface that is very nearly a surface of revolution. Accuracy of the parabolic curve can also be improved during this operation. To establish the optical axis precisely, the most accurate bearing obtainable should be used for rotating the mirror during surface generation.

A quick buffing operation to provide a reflective surface will permit testing for astigmatism by reimaging a pinhole through null corrector lenses from the center of curvature of the mirror. This test, which is later described in more detail, is quite sensitive to astigmatism and will permit a quick evaluation of astigmatism even though the accuracy would still be quite poor by optical standards. If the return image is circularly symmetric, the surface is a surface of revolution. If it is not, further interpretation by viewing the image inside of, and outside of focus, is often possible. In any case, the circular symmetry of the generated surface will be evaluated.

Care will be required during polishing to avoid developing sharp zones and to preserve and improve upon the surface of revolution. A basic problem in polishing deep aspherics such as this is caused by the fact that a perfect fit between the lap and work depends on the relative position of the two pieces. In polishing flats and spheres, the two pieces will fit, regardless of where the lap is placed on the work. Small laps are often used during parabolizing to minimize the amount of mismatch. A flexible tool can also be used to improve the fit, but it would be desirable to make the tool stiff in the circumferential direction to make it tend to maintain the surface of revolution. A small stroke also keeps the mismatch to a minimum.

An optical generating and polishing machine is being built as part of a classified Air Force program. The machine, as now designed, will not clear a 120 inch diameter mirror, but modifications to enlarge the clearance are feasible. The machine (which is not classified) has an externally pressurized hydrostatic oil bearing, and should be stable to 6 micro-inches radial runout with a wobble of the axis of rotation of less than 0.2 arc seconds. Tests of the table bearing have not been made at this writing. A motorized spindle is provided for generating, which traces a template to generate the desired curve. After completion of the generating cycle, the generating equipment is removed and replaced by a reciprocating polishing assembly.

Support of the mirror during the generating, polishing and testing is critical. During optical working, it is important that the mirror be supported reasonably uniformly, and in such a manner that the reactions to the external loads of polishing or generating are uniform in all azimuth directions. Otherwise, astigmatism may be introduced by the support. For testing, the support must be uniform enough that the mirror does not deflect due to its own weight by as much as one fourth of the accuracy to which the mirror is being tested. A satisfactory support for both optical working and testing can be obtained by providing a great many springs, each placed under the center of gravity of the segment of the mirror which it is designed to support. The springs must be soft enough and in great enough number that the differences in the forces carried by the springs, due to mechanical non-uniformities (non flatness of the surface the spring rests on etc.), do not deflect the mirror by more than 0.5 micro-inch in the present case. The springs can then be well damped by surrounding them with pitch, which serves to carry most of the transient load of polishing. The springs should preferably be designed to be stable under fairly high lateral loading so that the rotational driving of the mirror can be accomplished through friction with the pads on the springs. Pads of cork or rubber should be provided to avoid the thermal affects of metal in contract with the mirror. Rollers (with axis tangential) can be used to provide radial support. They should be centered vertically along the edge to minimize bending effects and should be uniformly spaced around the periphery.

After optical working, an interval of recovery time must be allowed to permit the springs to return to their equilibrium position before testing.

After the surface is polished, the figuring operations start. The purpose is to locally polish the high zones to bring the mirror to the desired curve. The main difficulty at this point is that of optically testing the surface to determine the actual curve. It will be necessary to figure the mirror to an accuracy of about 1/10 wave, or about 2 micro-inches (although the specification should be written in terms of the slope error or the energy distribution within the image). Testing a fast parabola to this accuracy presents some real problems and no single test can be considered completely reliable for the evaluation of the surface to this accuracy. Instead, a combination of many tests must be used, and the results compared to give confidence to the test results.

Common to all the test methods are the problems of atmospheric disturbance and vibrations. The optical path lengths will be long and turbulance or stratification of air within the optical path can make results unclear or distort the path.

These effects are caused by the variation of the refractive index of the air with temperature. The initial testing can be performed in air. A vertical testing position is preferred to minimize stratification effects; and this position is also convenient since it allows testing without removing the mirror from the spindle of the polishing machine. This is in keeping with the previous comments about provision of a support suitable for both testing and optical working.

As the figure of the mirror improves, atmospheric effects will become more troublesome despite the vertical testing position. For this reason, the optical path should be enclosed in sheet plastic (polyethylene or mylar) and the enclosed space filled with helium gas. Helium has a refractive index of 1.000036 as compared to 1.000293 for air. Since the refractive index of helium is nearer unity, variations in temperature in the helium will produce less variation of the refractive index, and the same turbulence will produce far less optical effects. As a final stage, it may be necessary to use a vacuum chamber, and it is advised that a vacuum chamber be used to check the assembled system even though it may not be needed during figuring of the primary mirror. Using a vacuum tank, atmospheric effects can be entirely eliminated. The disturbance caused by the atmosphere is roughly a straight line function of pressure, so that at 1.5 pounds per square inch absolute, the atmospheric effects would be one tenth of what they would be in air. This relation is complicated, of course, by the introduction of the vacuum chamber itself into the test set-up.

Mechanical vibrations also present difficulties during accurate testing of large optical elements. This problem is overcome largely by vibration isolation systems. The generating and polishing machine previously mentioned is mounted on a seismic block having a natural frequency of about 1.4 cycles per second. This serves to alternate vibrations of frequencies greater than 2 cps, the range of seismic disturbances. The structure supporting the test equipment is also mounted on the seismic block. The operator performing the test must be provided with a separate support. The tests vary somewhat in their sensitivity to vibration. Where the eye is the receiver, it can follow image motions up to about 5 cps, and interpretation of the image is possible even though photographic recording of the image detail is impossible. However, the Hartmann test, which depends on the precise location of spot images that are photographically recorded, averages out any vibrations that are present. In the present case, testing should be performed with the equipment mounted on a seismic block.

The tests that would be performed on the mirror would include:

1. The Foucault test using a null corrector at the center of curvature.
2. Viewing a pinhole image through null correctors.
3. Wave front shearing interferometry.
4. Scatter fringe testing.
5. Scanning of the collimated beam with an autocollimator.
6. Collimation with a large test parabola.
7. Hartmann test.

A description of each of these tests follows:

The Foucault knife edge test is a classic test and probably is used more than any other optical test. A knife edge cuts partially across the image of a pinhole or slit that is formed by the optical elements under test. The knife edge intercepts those rays that are inclined toward it, and the view past the knife edge shows shadow patterns that can be interpreted as high and low zones on the mirror.

The most basic arrangement is obtained in testing a sphere where the pinhole and knife edge are placed adjacent to the center of curvature and no additional optical elements are required. To test a parabola at its center of curvature, two null correcting lenses can be placed just beyond the vertex center of curvature. The pinhole and knife-edge are then placed beyond these lenses, and the pinhole is reimaged at the center of curvature. The difference in the behavior between the parabola and a sphere is compensated by the null lenses. Care must be used in fabricating and positioning the null lenses if accurate results are to be obtained. Under ideal conditions, the interpretation of errors on the order of .04 arc seconds may be questionable. The test will be extremely useful in the early stages of figuring, but confirmation of the results by other testing methods will be required during final figuring. The positioning of the null lenses is critical, and the lens position is measured mechanically. This provides a significant gain in the accuracy of the test over the often used method of determining the axial intercept of the reflected rays. It provides a check that is free of the influence of auxiliary optics. The caustic curve of the f/2 parabola is 11.25 inches long, and is

0.9375 inches from the axis at the furthest point. Therefore, a relatively large range of motion must be provided. The disadvantages of this test include the time required to cover a full radius, the difficulty in optically establishing the exact center of curvature of an area, and the mechanical alignment and measurement difficulties. While the test may approach the desired accuracy, complete reliance on this test is not warranted.

In wave front shearing interferometry, a nearly spherical wave front is passed through a beam splitter. One portion is rotated slightly with respect to the other, and the wave fronts are recombined.

Deviations from a truly spherical wave front can be seen as interference fringes if a monochromatic light source is used. Photographic recording is normally employed, and data is taken by measurement of the fringes on the photographic plate. Data reduction, to convert the data to the mirror contour, can be performed through a computer program. This test is quite promising as a means of evaluating the mirror surface.

In scatter fringe testing, a spherical wave front is formed at a focus by a scatter fringe plate (that scatters part of the light uniformly in all directions while allowing the remainder of the light to pass). The unscattered light is reimaged by the optical system under test, and a portion of this light is scattered to form a nearly spherical wave front. The two wave fronts are combined and an interference pattern is obtained. The test is somewhat similar to wave front shearing except that a spherical wave front forms a basis of comparison so that interpretation of the results becomes easier. The physical test setup becomes more critical, and the ability to test an f/2 cone (or even f/4 cone at the center of curvature) to detect tenth wave errors is questionable.

An interesting test that has often been proposed is to scan the collimated beam with an autocollimator. This test should be performed with a metal mirror. It consists of positioning a light source at the focus of the paraboloid, and intercepting the collimated light with a scanning pentaprism which directs the light to an autocollimator. Use of a long focal length autocollimator will provide sensitivity to measure small angular deviations of the collimated beam. The pentaprism is insensitive enough to small rotations to allow a mechanical scanning mechanism to be used even when testing to 0.05 seconds. The metal mirror has sufficient reflectivity to reduce the difficulty of the photometric problems. The most critical factors are the positioning of the light source in the radial direction, and the size of the light source. Positioning can be made non-critical by averaging the readings taken at equal radii on opposite sides of the center. Tests during the early stages of figuring might be automatically recorded using an automatic auto-collimator. However, for measurements to 0.1 second or better, there is no instrument now available that would fulfill the needs.

It is recommended that a final check for the completed system be performed using a collimator, preferably one that will fill the full 120 inch aperture. An alternative would be to use a large flat to autocollimate the system, but a collimator will also be useful to train an operator under conditions closely simulating those in space. Since a large collimator will be available, the primary mirror should be tested using this collimator, as well as at its center of curvature. Most of these tests can be used in assessing the mirror while testing with the collimator, as well as at the center of curvature.

The Hartmann test is a basic test often used as a basis for acceptance of a mirror. Its principal drawback is that it samples the surface at discreet points, and therefore doesn't evaluate the overall smoothness of the mirror. The plate measurements and data reduction are time consuming, although computers have speeded the data reduction considerably. In this test, a diaphragm having holes in a prearranged pattern is placed over the mirror. A point source of light at the center of curvature illuminates the spots of the mirror that are exposed by the diaphragm, and pencils of light from these holes converge at the center of curvature. Photographic plates, located ahead of and behind the center of curvature, intercept the pencils, causing spot patterns on the plates. Measurement of the various spot positions provides an accurate measure of the slope of the surface.

In performing this test on an f/2 parabola, the main problem will be in balancing the diaphragm hole size. If the hole size is increased, the aberrations become more serious; as the hole size is decreased, the diffraction effects become dominant. While rules of thumb have been ,obtained for the optimum hole diamter, these do not necessarily apply to a parabola as fast as f/2. However, it is felt that an accurate Hartmann test can be performed on the mirror.

5.0 ALIGNMENT

The most critical alignment problem is that of maintaining centration of the secondary mirror on the optical axis. For astrometry, the image center of gravity must correspond to the geometric center to avoid bissection errors. Decentration of the secondary mirror in a Cassegrain system results in a coma-like aberration. The length of the comatic image is given by:[1]

$$E = \frac{3m}{16F_c} (m^2 - 1)\,\delta$$

where

E = length of the comatic image

m = magnification of the secondary mirror

F_c = focal ratio of the Cassegrain system

δ = decentration of the secondary mirror

When the length of the comatic image exceeds three times the radius of the Airy disc, astrometric results are affected. Using this criterion, the tolerances on centration of the secondary mirror for the various configurations becomes;

- - - - - - - - - - -

[1] R. M. Scott, "Optical Engineering" Applied Optics 1, 388 (1962)

TABLE 5-1

Focal Ratio	Decentration Tolerance
f/8	.0004-in.
f/10	..0004-in.
f/15	.0002-in.
f/30	.0001-in.
f/100	.0001-in.

The tilt of the secondary about its back focus is not critical, and the actual tolerances on tilt are determined by the alignment sensing system. Longitudinal displacement of the secondary should be limited to the focal depth of the primary mirror or .00015-inches.

The concept of a manned telescope allows an operator to align the secondary mirror to the required tolerances by viewing the diffraction image of the star at the focal plane. The non-symmetry of the ima ge is first evident as a non-uniform light distribution in the rings of the diffraction pattern. When the secondary mirror is adjusted to the point where the eye cannot sense non-uniformity of illumination in the first diffraction ring, the secondary is then centered within the above listed tolerances.

Similarly, the axial spacing can be adjusted to minimize the size of the Airy disc. Thus the ability to see the diffraction rings of a star image represents a powerful tool in using the telescope.

The actual alignment might proceed in two steps. First, the telescope would be pointed toward a bright field of view (the earth or the moon), and a rough alignment would be obtained by centering the reflected images of the primary and secondary with reference to a mechanical draw tube at the focal plane. Second, the image of a star would be examined on axis under high magnification. As explained above, the necessary precision is obtained by viewing the diffraction pattern.

Calculations on the inertia of the system indicate that a man at the focal plane can view a star image. The man would introduce low frequency vibrations into the instrument if he were physically attached to it, but his eye would probably be able to follow the motion of the image if he minimized his own motion. The success of this operation does depend on careful design of the hardware to avoid low frequency resonances. If it should be determined that it is impractical for a man to view the image directly, an image relay device could be used.

Calculations of thermal distortion of the structure have shown that there will be a cyclic warping of the structure which will move the secondary mirror radially about 0.025-inches total amplitude with a period of about 90 minutes (obtained by assuming that the maximum temperature gradient across the structure is about 4°F). It appears to be impractical to attempt to reduce this value by additional thermal shielding or by a thermal compensating structure, as either alternative would increase the weight and have questionable reliability. Therefore, an alignment system must be provided which will sense and correct the position of the secondary with respect to the primary mirror once the correct position has been determined by the methods already described.

The positioning of the secondary mirror must be controlled in five degrees of freedom (rotation of the mirror about the optical axis not having any affect on the system). Thus, five measurements must be made to "fix" the position of the secondary. These measurements are: three length measurements between the edge of the primary mirror and the secondary mirror assembly, and two tilt measurements made by two single axis automatic autocollimators. An isometric schematic sketch of the system is shown in figure 5-1. The two separate one-axis autocollimators are used rather than a single two axis unit to reduce the sensitivity of the measurements to rotation of the secondary about the optical axis. The automatic autocollimators will require some development which will essentially adapt presently existing instruments for this application. It would be desirable to separate the elements requiring critical positioning (the objective, beam splitter, and focal planes), and attach these directly to the primary mirror. The heat producing elements would be mounted separately and thus be well isolated from the main optical elements.

The distance measurements are made by Michelson interferometers, as shown in Figure 5-2. The beam splitter divides the light, some going to the corner reflector attached to the secondary mirror, the remainder going to the other corner reflector which serves as a reference. The corner reflectors return the beams which are recombined at the beam splitter and produce interference fringes. The phase wedge serves to display the fringes as parallel dark and light bands which are sensed by several photomultipliers. More than the two sensors shown in the schematic sketch will be required, as will be evident from the discussion which follows.

When the distance is changed by one-half the wave length of the light, the interference fringes will move by a distance equal to one fringe width. The use of multiple sensors allows sensing of the direction of the motion and interpolation between a fringe.

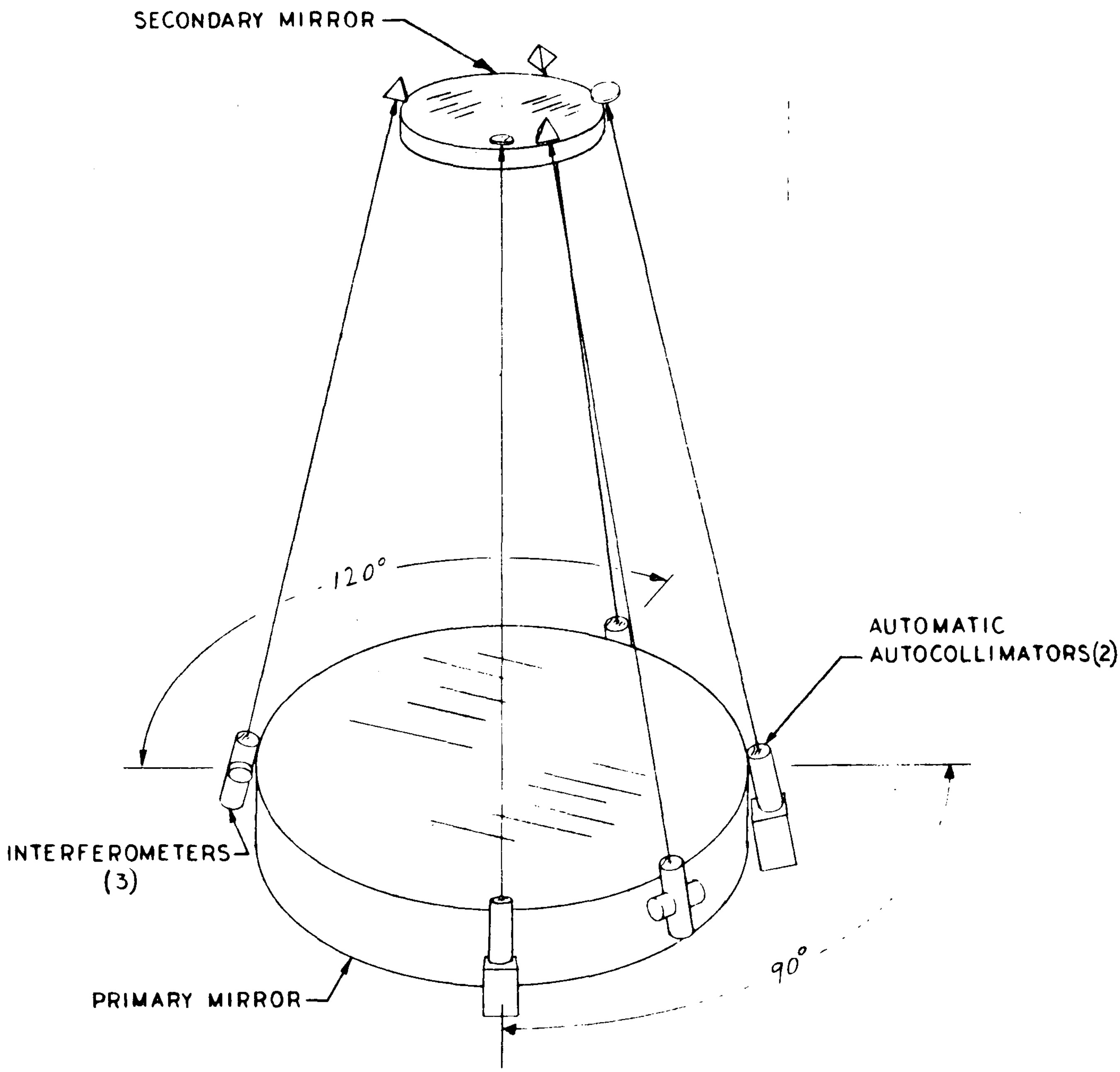
If the reference path length were equal to the working path length, a conventional monochromatic light source could be used. However, space limitations and problems of stability of the system make it mandatory that a short reference path length be used. This is entirely feasible if a laser is used as the light source. Dependable gas lasers operating in the vicinity of 6000 Angstroms are now available. The size of the smallest available unit is decreasing, so it is felt that, for a program that will necessarily finish several years hence, the interferometer is feasible.

This application for an interferometer is ideal in that two of the usual bothersome problems will be well under control. The high vacuum environment will eliminate turbeulence from consideration, and vibrations will necessarily be of small amplitude in the telescope.

In order to hold the secondary mirror to within the tolerances stated, the sensing units must be able to sense a small fraction of this movement. The alignment procedure will probably not align the mirror to the center of the tolerance range. If the servo system is allowed one-half of the total tolerance as a working range, the sensors will have to sense a movement equal to about one tenth the total tolerances, or 10 micro-inches radial movement and 15 micro-inches axial movement. Because of the unfavorable angle for determining radial movement with the interferometers, 10 micro-inches of radial movement corresponds to about 2.7 micro-inches change in path length at the interferometers. This corresponds to about one fifth fringe for 6000 Angstrom light. This amount of interpolation seems quite reasonable.

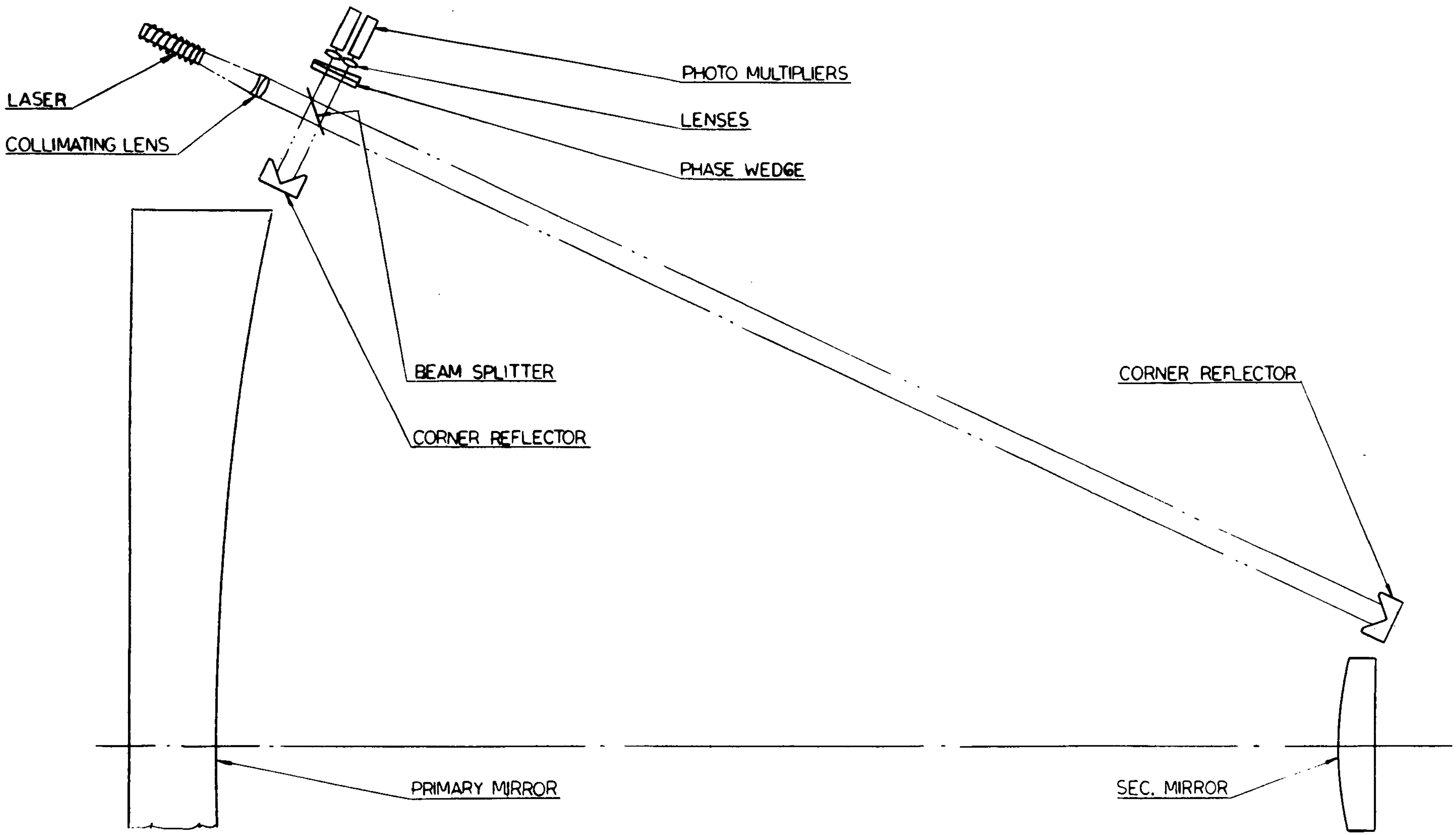
The rotation of the secondary mirror that would not affect the interferometers would be about an instantaneous center determined by the intersection of the axes, along which the interferometer measurements are made. This can be made to be the prime focus of the primary mirror, thus making the sensitivity of the automatic autocollimators quite non-critical. And in the present state of the art, sensitivity to one tenth arc second is obtained in commercially available instruments.

First order image motion due to motion of the primary mirror during long exposures may reduce resolution. The best resolution of the unit will no doubt be obtained by short exposures during which time the actuators for positioning the secondary mirror remain inactive. For longer exposures with the alignment system operating, there will necessarily be some loss of resolution. The estimated maximum lengths of exposure without loss of resolution due to thermal warping of the structure, varies from about 2 seconds to 30 seconds, depending on the position in orbit at the time of exposure.



SECONDARY MIRROR
120°
AUTOMATIC
AUTOCOLLIMATORS(2)
INTERFEROMETERS
(3)
90°
PRIMARY MIRROR

FIGURE 5-1



120-INCH ORBITING TELESCOPE FOR N.A.S.A.

SCHEMATIC OF INTERFEROMETER FOR
POSITIONING SECONDARY MIRROR

J. W. FECKER DIVISION AMERICAN OPTICAL CO.

FIGURE 5-2

6.0 STRUCTURE

The function of the structure is to maintain the proper space relationship between the optical elements, or at least to maintain these relationships closely enough to permit the alignment system to perform its function. Vibrations are critical during operation. The structure must also provide support for the optical elements through the launch phase, and it is this requirement that determines much of the structure. In addition, the unit must be tested in an environment with gravity.

Almost all the requirements favor a stiff structure having natural frequencies as high as possible. A large amount of damping is preferable with as much of the damping in the dimensionally less critical regions as possible (this avoids the problem of instrumentation not remaining stable because of the Coulomb damping effects). A high thermal conductivity and low weight are desirable. As discussed in more detail in the "Thermal Analysis" section, the thermal distortions of the structure provide the greatest disturbance to the telescope. There will be thermal gradients and variations in the mean temperature which will bend the structure and vary the spacings between the elements. Thermal shielding is provided to control the structural distortion to reasonable values, this being achieved by holding the thermal gradients to no more than 4°F difference in temperature between any two points on opposite sides of the satellite.

The optical design has placed the primary mirror, the refracting elements, and the focal plane close enough together that an aluminum alloy connecting structure will serve to maintain the spatial relationships in these thermal environments without additional compensation. The secondary mirror, however, is both far away and critical in its positioning. A separate automatic alignment system is provided to maintain a constant spatial relationship between the primary and secondary mirrors. This greatly reduces the requirement on the main tube structure for dimensional stability. An aluminum alloy, honeycomb sandwich tube is used for the main structure. This construction provides a relatively stiff structure with excellent damping characteristics.

The structure is made almost entirely of aluminum alloys. The use of a single material avoids problems caused by differential expansion under the varying temperature conditions. Aluminum has the advantages that: (1) excellent strength to weight ratios are available, (2) it has a high thermal conductivity, (3) it is easily worked, and therefore available in many forms, (4) it is ductile, and therefore more easily designed to withstand the launch environment, (5) a wide range of surface absorbtivities are available by common surface treatments, and (6) it is non-magnetic. These advantages are sufficient to overcome the slight disadvantages of the high thermal coefficient of expansion and low elastic modulus.

During operation, the following will be vibration inputs to the structure:

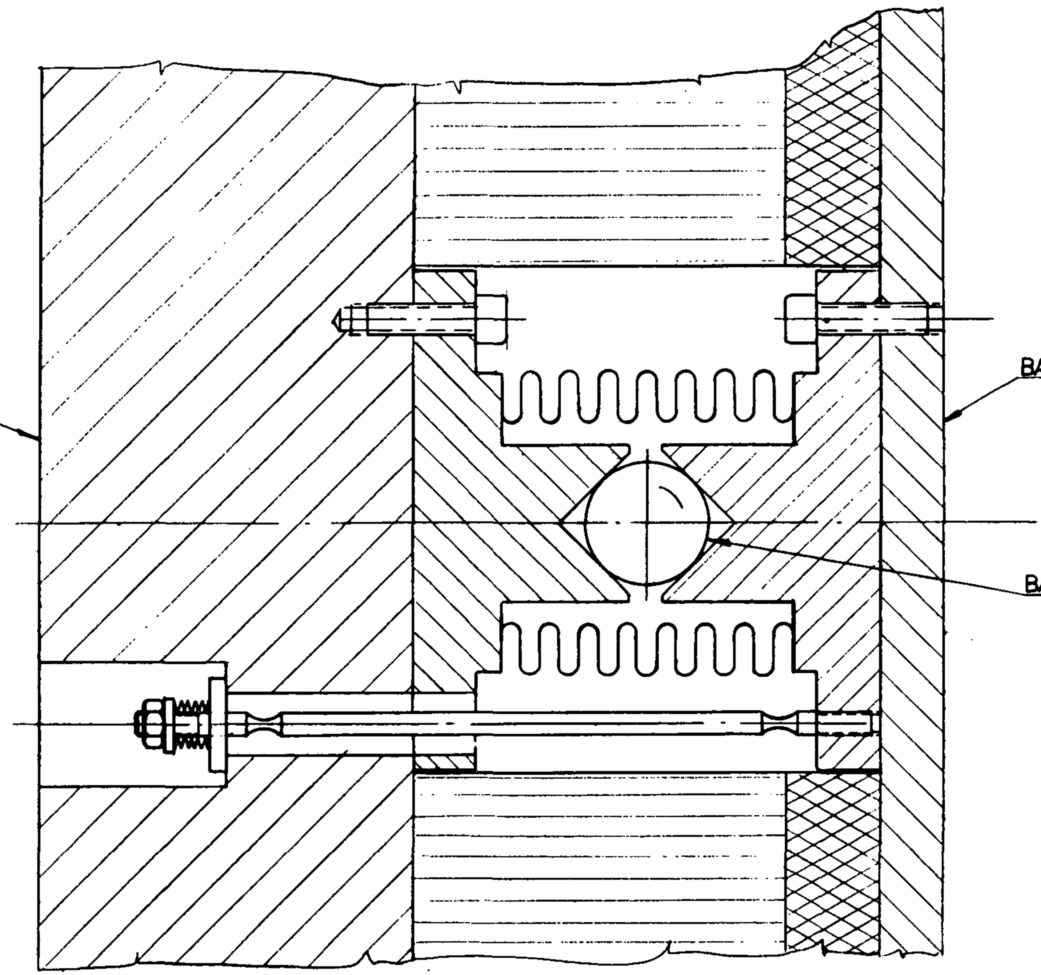
1. The inertial wheels and gas jets used for stabilizing and pointing.
2. Mechanical modulators for the guidance system star trackers.
3. The secondary mirror positioning fine pointing actuators working at the focal plane.
4. Any moving parts in the experimental package.

While it is anticipated that the operator will perform alignment functions at the telescope, he will not be in contact with the structure during operation, therefore he is not considered as a vibration input to the structure. It can be shown that in order to move the entire telescope structure 0.01 arc seconds, a one pound mass would need to be moved only 0.072 inches in a direction perpendicular to the optical axis at the focal plane. While it could not be expected that a man would remain this still if in contact with the structure, it is apparent that the large mass of the telescope is quite helpful in making mechanical disturbances from these various vibration inputs less critical. It would appear that motion of the entire telescope structure caused by these vibration inputs will be negligible. The remaining problem is one of avoiding resonance in the structural members. Study of the interactions between structural vibrations and the various servo systems using an analog computer will be necessary.

The launch mode will be as similar to the operating mode as is possible to minimize the conversion to be made by the operator. Additional bracing and damping of the secondary mirror assembly will stiffen and protect it, particularly against torsional oscillations about the optical axis.

During launch, the primary mirror will be held down with cushions bearing against the front surface at the outer 10" of periphery of the mirror. The back surface will be supported by segmented bladders, inflated and with air pressure control so as to maintain a constant preload on the mirror. With the mirror held in this manner, its natural frequencies in bending are 300 cycles per second or higher, and the mirror can withstand a loading of 18 g's without exceeding a unit stress of 300 psi in the beryllium. Tests of micro-yielding of beryllium have indicated a micro-yield point of 300 psi. Radial support will be provided during launch by a number of bladders bearing against the outer periphery of the mirror. In addition, the center portion of the mirror will be somewhat dampened by a bladder bearing against the central hole of the mirror and the central tube. All these bladders are to be removed after the launch by the operator, and the bladder support will be replaced by a three point kinematic support which will control the position of the primary mirror without overconstraint. The primary mirror supports are shown in Figure 6-1, and consist of hardened steel balls rolling in radially oriented grooves. The balls are enclosed by flexible metal bellows which retain some lubricant to insure that no welding will take place. The mirror is held against the steel balls by springs.

The four vane spider suspends the secondary mirror assembly and the focal plane at prime focus. The four vane spider is generally standard for telescopes because it produces less diffraction effects in the image. This conventional configuration does have the disadvantage that the stiffness resisting torsional oscillation of the secondary mirror assembly is quite low. For this reason, Orbiting Astronomical Observatories have made use of a modified spider which somewhat sacrifices the diffraction effects for a stiffer mounting of the secondary. In the present case, added bracing will stiffen the secondary mirror mount through the launch phase, and will be removed by the operator immediately after launch.



120-INCH ORBITING TELESCOPE FOR N.A.S.A.

PRIMARY MIRROR LOCATORS

J. W. FECKER DIVISION AMERICAN OPTICAL CO.

FIGURE 6-1

After the bracing on the secondary mirror is removed, the order-of-magnitude values of natural frequencies for the secondary will be 10 cps for torsional oscillation about the optical axis, 100 cps for rotations about a diameter, and 80 cps for translation along the optical axis. The final values should be low enough that the fringe counters used in the interferometers will be able to follow the vibrations (otherwise the system will be difficult to align with the operator present), yet should be as stiff as possibe. Good damping is desirable since absolute positioning is not dependent on the stability of the spider elements. Damping can be provided in the fastened joints, and by use of laminated materials.

Tensioning the spider vanes provides a means of controlling the natural frequencies of the secondary. The tension is provided by two spring assemblies. Mechanical actuators, described in the "Alignment System" section, provide a means for fine alignment in space.

120-INCH ORBITING ASTRONOMICAL TELESCOPE

WEIGHT BUDGET

Primary Mirror	1800 lb
Primary Mirror Cell	2800 lb
Structural Tube Assembly	2000 lb
Thermal Shielding	1500 lb
Secondary Ring, Spiders, Mount and Secondaries	1850 lb
Refractors and Mounts	750 lb
Baffles and Shielding	520 lb
Alignment Sensors	500 lb
Bladders and Auxiliary Launch Supports	370 lb
Electronics	200 lb
	12290
Experiments (Including guidance sensing at focal plane)	2500 lb
Guidance, Auxiliary Life Support, etc.	5000 lb
TOTAL	19790 lb

7.0 THERMAL ANALYSIS

Thermal gradients within the satellite will affect both the structure and the optical elements. The most damaging effects will be caused by the transverse gradients. These will warp the structure causing decentering of the secondary mirror and tend to cause astigmatism in the mirrors. The ambient temperature for the telescope is considered and the problem of distortion of the primary mirror caused by alternate viewing of space and the earth has also been investigated.

For simplicity, it has been assumed that a transverse thermal gradient will exist within the structure, and that the temperature of any point in the structure is directly proportional to the distance from a neutral axis which is at the mean temperature of the structure. The maximum temperature difference between points on opposite sides of the structure is $(\Delta T)_L$. The transverse gradient will cause the structure to bend to a radius R with the center of curvature on the cool side. R can be determined:

$$R = \frac{d}{n\,(\Delta T)_L}$$

where

n is the coefficient of expansion of the structure

and

d is the diameter of the structure.

The deflection at the secondary mirror due to the transverse gradient is:

$$= \frac{h^2}{2R} = \frac{(\Delta T)_L n h^2}{d}$$

where

h is the length of structure between the primary and secondary mirrors

The tilt of the secondary can also be determined:

$$\Theta = \frac{1}{R} = \frac{nh\,(\Delta T)_L}{d}$$

In the case of the orbiting telescope, $(\Delta T)_L$ will vary in time as will the direction of the gradient. For purposes of calculating the motion of the structure as inputs to the alignment system, it was assumed that $(\Delta T)_L$ varied sinusoidally with time having a 90 minute period. The calculated temperature time relationships for the OAO indicate that this is a reasonable assumption. Inserting values for an aluminum structure of 130 inch diameter and 200 inches long results in a decentration of .025 inches for a $(\Delta T)_L$ of $6^{\circ}F$. It is within the capacity of the alignment servo to handle motions of this magnitude and it should be possible to shield the structure to keep the gradients to this value.

The astigmatism produced by thermal gradients within the structure will be negligible if the three-point mounts are made to be thermally insulating and if the entire surface of the mirror is aluminized to minimize radiative transfer of heat between the mirror and the structure. Calculations show that the temperature gradient in the mirror (using dimensions assumed in this study) will be less than that of the structure by a factor of about 200 under steady state conditions. With the high heat capacity of the primary mirror and the transient conditions obtained in the structure, the transverse gradients will be even less. Under the steady state conditions, a gradient of $(\Delta T)_L = 8^{\circ}F$ in the structure could be tolerated.

A specific ambient temperature for the telescope cannot be recommended without further study and experiments. A great many factors favor a low temperature. Receivers perform better, the thermal conductivity of the structure and mirrors increases while the coefficients of expansion decrease. However, the primary mirror is made with three materials; the beryllium base metal, the Kanigen coating on the surface and the silver-lithium brazing material used to attach the back face plate. Tests would be required to assure that no distortion of the mirror would be caused by bi-metal effects before a specific temperature can be recommended.

An important question is whether the alternate viewing of space and the earth will distort the primary mirror sufficiently to cause a loss of available exposure time. It is assumed that the mirror is at a temperature of $460^{\circ}R$ and it has an emissivity of 0.05. The area factor will be about 0.045 at the center of the mirror and 0.040 at the edge. When viewing space, assumed to be at absolute zero, the mirror will radiate 0.0174 Btu per $ft.^2$ hr. When it views the earth, with an effective black body temperature of $460^{\circ}R$, the net transfer is zero. The heat that is radiated to space is received by the mirror as radiation from the structure at both front and back surfaces. Therefore, about half of the heat must be conducted from the back surface, thus establishing a front-to-back thermal gradient through the mirror and changing the radius of curvature. For small gradients such as this, there is no optical degradation other than defocussing. Thus a small steady state gradient is permissible.

The mirror will alternately see space and the earth for periods of about 45 minutes each in the most severe condition as far as thermal disturbances are concerned. The average heat exchange through a cycle is a loss of about 0.0087 Btu per ft.^{2} hr. which might be considered a steady state or average condition. The deviation from this condition will be by a flux of $\pm$ 0.0087 Btu per ft.^{2}hr. for periods of 45 minutes giving a net heat exchange during a half cycle of .0065 Btu per ft.^{2}. If this amount of heat were instantaneously introduced into the front face plate, the temperature would rise by 0.0002°F. If this value existed as a thermal gradient across the mirror, it would result in negligible focal shift. Therefore, it is quite safe to assume that no exposure time will be lost due to the thermal transients within the mirror.

8.0 MICROMETEOROID DAMAGE

The optical element most vulnerable to micrometeoroid damage is the primary mirror. A micrometeoroid that impinges at very high velocity directly on the mirror surface will penetrate, causing spalling from the back surface. The damage, in optical terms, will be a small hole in the reflecting surface that will cause a diffraction image at the focal plane. It is improbable that the surface surrounding the hole will be distorted.

The optical effect of many pits will be directly proportional to the total area of the pits. Since each pit is small, its Airy disc will be large compared to the Airy disc of the system. If the number of pits were allowed to increase to the point where the intensity of the diffraction images of the pits was equal to the intensity of the main diffraction image, the resolution would correspond to that of a system having an aperture equal in size to the average pit diameter. This, of course, would be an extreme case. It seems reasonable to consider that the system will no longer diffraction limited when the illumination due to the'background (scattering due to the pits) is equal to the illumination in the first diffraction ring. When this condition is obtained, it becomes somewhat questionable as to whether the optical elements can be aligned by viewing the diffraction rings. With this assumption, the life of a diffraction limited system will be:

$$T = \frac{.0175}{S}$$

where

T = life in years

.0175 = the relative illumination in the first diffraction ring

S = the fraction of the total area that is pitted in one year

The method used to calculate the value of S was recommended by Mr. John R. Davidson of NASA Langley. From an estimate of meteoritic flux (Whipple's 1957 estimate[1] was used as it is the most conservative of the recent estimates) the kinetic energies of each size group of meteoroids was calculated. Each impact produces a pit, the volume of which is proportional to the kinetic energy of the particle. No constant of proportionality was available for Kanigen, but it was assumed that the constant would be close to that for hypervelocity impact on steel.[2] By assuming that the craters were hemispherical, a relation between the volume and

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(1) As tabulated in NASA TN D-1493

(2) The constant for steel was obtained from Rinehart and Pearson, "Behavior of Metals Under Impulsive Loads" ASM 1954

diameter of a pit obtained. Multiplying the area of a single pit by the frequency of impacts for each meteor visual magnitude the value of S for an unshielded mirror was obtained. The life of an unshielded mirror would be 11 years. Since the primary mirror is surrounded by a tube structure which will intercept all but about 3% of the incident meteoroids, the predicted life of the mirror becomes about 300 years.

It is interesting to note that the greatest damage is done by the smallest particle because of their greater frequency. However, there are no meteoroids of less than about one micron diameter, since for these extremely small particles, the solar pressure exceeds the solar gravitation and the particles are blown away from the solar system.

9.0 GUIDANCE INPUTS

The scope of the present study is limited to the determination of the availability of guide stars that might be used. The original concept of the telescope, before any study was made of the configuration, was one having an extremely narrow field. The optical configuration that were obtained had larger fields so that, except for experiments with the f/2 or f/8 configurations, there should be sufficient guide stars within the corrected field for guiding.

Estimates indicate that with a 120 inch aperture, stars of the sixteenth magnitude will provide sufficient light for guiding. Of course, response time can be improved by use of brighten stars. Estimates[1] indicate that there are 1500 stars per square degree (mean value) of sixteenth magnitude. If the guiding signal is obtained by splitting each star image into two parts and balancing the light between the two, three guide stars are required for a complete fix of the telescope position. Based on sixteenth magnitude stars mean density there would be between 4 and 5 guide stars in the f/8 field. In regions of low star density, it is likely that there would not be 3 or even 2 stars

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[1] Seares, Van Rhijn, Joyner and Richmond, Astrophysical Journal 62, 320 (1925)

within the corrected image. In this event, a comatic image outside of the corrected field might be divided in a radial direction. This divides the image about its axis of symmetry and permits guiding from an otherwise unusable image. The curved field of the f/30 configuration presents no problem in guiding as the guiding sensors can be focussed independent from the experiment.

APPENDIX II

APODIZATION

APODIZATION

An important branch of astronomy is the measurement of double stars, but many double stars are too close together to be resolved from the surface of the earth. A large orbiting telescope might make a real contribution toward this problem, but in a telescope free of atmospheric turbulence, the image of a star is a small disc (the Airy disc) surrounded by rings of decreasing brightness. A weak star close to a bright one may be invisible if its image lies in these rings. This problem is of little practical importance for ordinary telescopes where the blur of the air washes out the rings, but in the orbiting case, diffraction may set the limit on what can be seen, and it is appropriate to ask if anything can be done about it. As part of this study, a preliminary investigation was carried out which is summarized here.

The primary mirror of a telescope is normally the aperture stop, and one might expect to apply the apodization to it; but apodizing requires discarding some of the light, and would penalize other experiments not needing the effect. If an optical system is used to observe an object on the axis, any part can be called the aperture stop, and in particular, a secondary mirror can be specially apodized for this purpose, or an apodizing filter can be inserted near the focal plane.

The mathematical relation between the functions which define the geometry, phase, and amplitude of the aperture (the pupil or aperture function), and the spread function of the image of a point, is a Fourier transform.

Let us assume F (β γ) is the exit pupil function and U (x, y) is the amplitude of illumination in the image plane.

Then $$U(x, y) = \mathcal{T}\left[F(\beta, \gamma)\right] \tag{1}$$

The pupil function is generally:

$$F(\beta, \gamma) = A(\beta, \gamma) e^{-ik\Delta(\beta, \gamma)} \tag{2}$$

where

A (β, γ) represents the out-going wave amplitude,

$e^{-ik\Delta(\beta,\gamma)}$ represents the phase, and

$\Delta(\beta, \gamma)$ is the system's wave aberration.

The illumination produced by a point in the image plane is

$$E(x, y) = U(x, y)\, U^*(x, y) \tag{3}$$

where * represents the complex conjugate.

For a geometrically perfect system (diffraction limited) and without defocusing .

$$\Delta(\beta, \gamma) = 0 \tag{4}$$

If the transparency of the system is uniform across the exit pupil

$$A(\beta, \gamma) = 1$$

With these simplifications, the image of a point produced by a system with circular pupil is the classical Airy disc.

$$E(x,y) = \left[\frac{z\,J_1(z)}{z}\right]^2 \tag{5}$$

where J_1 is the first order Bessel function, and

$$Z = \frac{\pi}{\lambda} \quad \frac{D}{R}\,\rho \tag{6}$$

where: D = clear aperture of the system

R = focal length

ρ = polar radius in the diffraction image

For a system that is diffraction limited, and has uniform transparency and central obscuration, the illumination expression becomes:

$$E(x\;y) = (\alpha_2)^4 \left[\frac{z\,J_1(z_2)}{z}\right]^2 + (\alpha_1')^4 \left[\frac{z\,J_1(z_1)}{z_1}\right]^2 - 2\,\alpha_1'^{\,2}\,\alpha_2^{\,2}\;\frac{z\,J_1(z_1)}{z_1}\;\frac{z_2\,J_1(z_2)}{z_2} \tag{7}$$

where

α_2' is the system's semi-aperture angle

α_1' is the obscuration's semi-aperture angle

$$\alpha_2' > \alpha_1' \tag{8}$$

$$Z_i = \frac{2\pi}{\lambda}\,\alpha_i'\,\rho \qquad i = 1, 2 \tag{9}$$

This is the case of the reflecting telescope with a secondary mirror obscuring part of the aperture.

The resolving power for optical systems with the same diameter changes with the obscuration (120" in the present case).

The effects of the obscuration are:

1. To decrease the radius of the first black ring.
2. To decrease the illumination in the central maximum.
3. To relocate the rings.
4. To increase the illumination in the secondary rings.

Considering only #1, and the Rayleigh criterion, the resolving power increases with the obscuration, but, considering the Sparrow criterion, the resolving power decreases. That is, the telescope is improved or degraded according to what you are trying to do with it.

The angular resolving power (Rayleigh) for a 120" telescope without obscuration is 0.042 seconds of arc for a wavelength of 0.5 microns. This is the radius of the Airy disc to the first dark ring.

For a Cassegrain system, 120" and 25% obscuration, the angular resolving power is .03825 seconds of arc.

Because central obscuration both reduces the light in the Airy disc and increases the light in the rings around it, the loss in contrast is more striking. Without obscuration, the first ring is 1/57 as bright as the center of the disc; with 25% obscuration, it is 1/24 as bright.

Hence, without obscuration, a companion star, 57 times fainter than the main star, will be obliterated in the first ring. However, a companion star 27 times fainter than the main star, will be obliterated in the first ring for a cassegrain system of 25% obscuration.

By apodizing the system it is possible to reduce or eliminate this problem.

The apodization can be achieved in three different ways:

1. By changing the size and shape of the exit pupil
2. By changing the transmission, A (β, γ), in expression (2)
3. By changing the phase locally, in expression (2)

It is not possible to prescribe a general apodizing. It is always necessary to apodize for particular cases.

In the present case the problem is to apodize a Cassegrain system of 120" aperture operating at f/30 for detecting double stars 0.08 to 0.16 seconds of arc apart. Stars further apart will be relatively easy.

There is great deal of theoretical literature on this subject by Luneberg, Barakat, Lansraux, Boivin, Steel, Maréchal, and others. The various papers differ in the assumptions that are made and the task that the author sets himself. None of the papers exactly describes the present problem, which is to suppress the light in the first two or three rings around the Airy disc, without broadening the disc appreciably and without too much loss of light.

Luneberg[1] in particular posed a series of particular problems:

1. What pupil function gives the greatest intensity at the center of the image for a given total energy?

2. What pupil function gives the greatest intensity at the center for a given total energy and a given distance to the first dark ring?

3. What pupil function puts the most energy into a given circle?

Barakat[2] has reviewed work since 1944 on these problems.

Question #1 has been explored in detail by Jacquinot for specifications in spectroscopy.

Questions #2 and #3 have been treated by Luneberg, Osterberg, Barakat, Lansraux, Boivin, and others (see Barakat, loc. cit. for references). In all cases, they deal with optical systems without obscuration.

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[1] R. K. Luneberg, Mathematical Theory of Optics, Brown University Mimeographed Lecture Notes, Providence, 1944, pp. 386-395.

[2] R. Barakat in Advances in Optics, North-Holland, Amsterdam, 1961, pp. 67-108,

For such systems, the best apodization, as far as we know, has been achieved by Lansraux[3], using transparency functions generated by general polynomials up to the 10th degree. For the stars 0.08 seconds apart, the Lansraux apodization could provide a gain in Sparrow resolution of as much as 100, assuming the differential threshold and the latitude of the photographic emulsion are adquate.

To illustrate the situation, and our preliminary and partial understanding of it, see Figures II-1 and II-2. In Figure II-1 we can see the influence of the Cassegrain central obscuration compared with a clear aperture, both passing the same energy, i.e. the exposure in the second case is $(1/4)^2$ longer than in the first. It will be seen that 25% obscuration produces a small but not trivial effect.

Figure II-2 shows what can be done by Lansraux apodization for unobstructed apertures . The picture is much enlarged compared with Figure II-1. It will be seen that light can be squeezed almost completely out of the first diffraction ring and contrast can be much increased for a chosen location of the second star.

It should be emphasized again that Figure II-2 does not include any allowance for the influence of central obscuration,which is the whole point of Figure II-1. Calculations for this case are laborious but not otherwise forbidding. However, the better indication is to reduce the central obscuration as much as possible.

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[3] G. Lansraux, Diffraction Instrumental, Editions de la Revue d'Optique, Paris, 1953

In particular, high resolving power is apt to demand a very long focal length to avoid the grain of the film, and such a long focal length requires large magnification at the secondary, approximately 20 to 50 times. Such a secondary mirror need not obscure more than about 1/20 to 1/50 of the aperture, which is negligible. The only obstacle to keeping the obscuration small is mechanical, not optical.

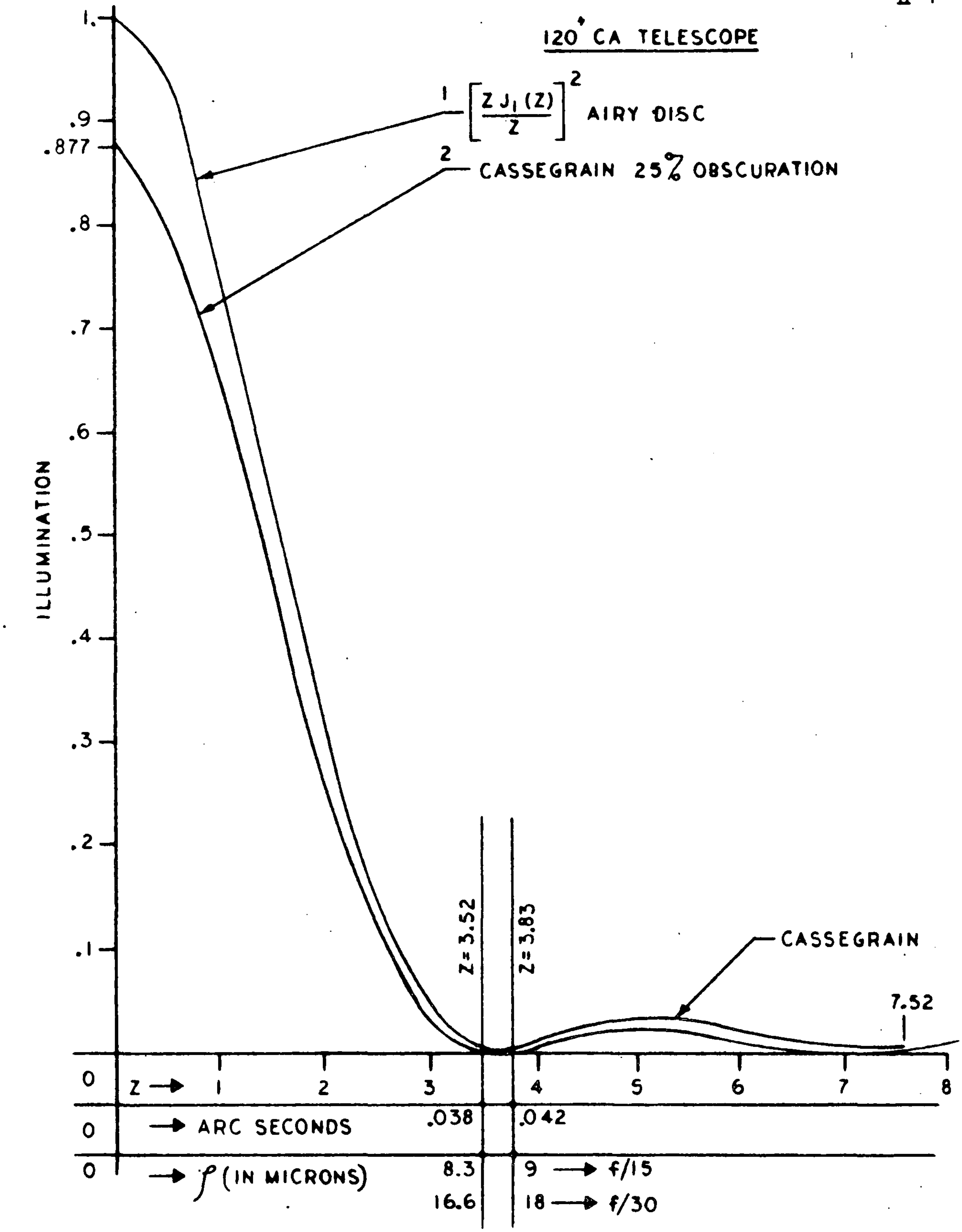
120" CA TELESCOPE
1 $\left[\frac{Z J_1(Z)}{Z}\right]^2$ AIRY DISC
2 CASSEGRAIN 25% OBSCURATION
ILLUMINATION
1.
.9
.877
.8
.7
.6
.5
.4
.3
.2
.1
Z=3.52
Z=3.83
CASSEGRAIN
7.52
0
Z → 1 2 3 4 5 6 7 8
0
→ ARC SECONDS
.038
.042
0
→ ρ (IN MICRONS)
8.3
9 → f/15
16.6
18 → f/30

FIGURE II-1

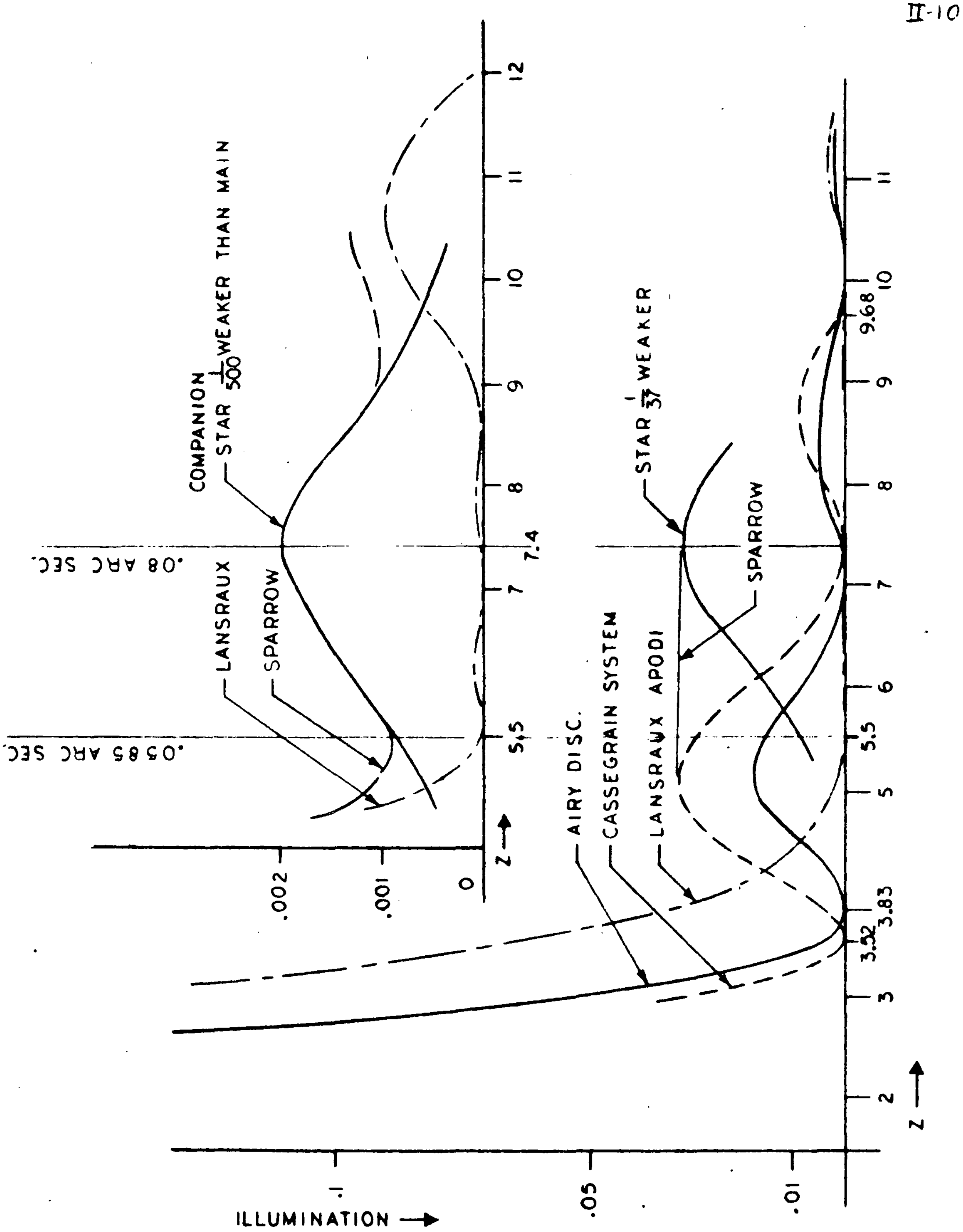
COMPANION STAR 1/500 WEAKER THAN MAIN
LANSRAUX
SPARROW
.08 ARC SEC.
.0585 ARC SEC.
.002
.001
0
Z →
5.5
7
7.4
8
9
10
11
12
AIRY DISC.
CASSEGRAIN SYSTEM
LANSRAUX APODI
STAR 1/37 WEAKER
SPARROW
.1
.05
.01
ILLUMINATION →
Z →
2
3
3.52
3.83
5
5.5
6
7
8
9
9.68
10
11

FIGURE II-2